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# The effect of wake position and yaw misalignment on power loss in wind turbines

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**Abstract.** For a single wind turbine, the efficiency of extracting energy from the wind depends on the ability to align the wind turbine with the dominating wind direction. Considering average power production, yaw misalignment is relevant when the wind turbine operates with maximum power coefficient. On the other hand, the power production is less sensitive to yaw misalignment in high wind speeds, where the available energy in the wind field is higher than the maximum wind turbine capacity. In a wind farm, the interaction between nearby wind turbines alters the flow, and the power production is reduced. The present study investigates how yaw misalignment affects the power production in these wake situations compared to yaw misalignment effects for a wind turbine in the free-stream. Two generic cases are presented in this paper, offshore and forest, where the atmospheric conditions alter the morphology of the wake and, therefore, the power output of a yawed wind turbine operating in wake conditions. The results show that, for a conventional downstream spacing further than 3 rotor diameters, yaw misalignment results in larger power loss in wake situations than in free-stream. In wake situations, the presented results also show that the spatial distribution of the deficit influences the relative power loss when the wind turbine is operating in yawed conditions.

## 1. Introduction

To achieve the maximum profitability in a wind farm, the wind turbine design, farm layout, and operation strategy must be optimised in an integrated manner. An efficient wind farm design takes into account the influence of the wind turbines on each other, typically with a focus on wake effects. The detrimental effects of wakes on power output and loads in a wind farm can not be completely eliminated, and therefore it is important to consider the best way of operating a wind turbine in these situations. This paper presents a thoughtful explanation on the effect of yaw misalignment on the power output of a wind turbine when operating in a wake case. The findings can be used in the design of both the wind farm and its control system.

The yaw angle of a wind turbine relative to the incoming wind direction plays a significant role in the loads and power production. Significant fatigue reductions can be achieved with an active yaw controller as shown in [1] and [2]. These strategies, although beneficial in reducing loads by purposefully inducing a yaw misalignment, sacrifice power output in the partial load regime. A key finding, which is presented in this paper, is how the power deficit as a function of yaw angle varies in wake conditions.



In literature, power loss due to yaw misalignment is typically defined as being proportional to a factor of  $\cos^\alpha \gamma$  [3], where  $\gamma$  is the yaw angle and  $\alpha$  is constant exponent term. In uniform flow conditions,  $\alpha = 3$ . However, measurements and simulations show that the value of  $\alpha$  varies for unsteady wind speeds. Different studies have found the  $\alpha$  parameter ranging from  $\alpha = 1.8$  to  $\alpha = 5.14$  [4][5], depending on atmospheric and turbine operational condition. As part of the investigation in this paper, the value of  $\alpha$  is determined for wind turbines in full wake situations.

## 2. Methodology

Wind turbine simulations for this investigation are performed using the HAWC2 aero-servo-elastic code [6]. HAWC2 is based on blade element momentum theory extended with sub-modules such as dynamic stall, dynamic inflow or skew angle among others [7]. The structural part consists of a multi-body Timoshenko beam formulation defined with a floating reference system.

A generic 2.3MW wind turbine model is coupled with the open-source DTU wind energy controller [8]. The simulated wind turbine is a collective pitch regulated, variable speed turbine with a rotor diameter of 90 m and a rated power of 2.3 MW at 12 m/s. The spectral tensor Mann model [9] was used to generate the background wind field. The electrical power output is obtained by means of HAWC2 as averaged time-series data.

A wake situation is generated by performing simulations with an upstream, wake-generating wind turbine, and a downstream wind turbine located at a predetermined location behind the first wind turbine. The unsteady inflow conditions experienced by the upstream wind turbine are transported to the downstream wind turbine using the Dynamic Wake Meandering Model (DWM) [10, 11]. Thus, the downstream wind turbine feels a disturbance of the original turbulent inflow due to the wake.

The simulated cases are run for an offshore case ( $TI = 6\%$ ) [12], and a high-turbulence forest case ( $TI = 22\%$ ) [13] [14]. The different turbulence intensities were achieved by scaling the turbulent wind fields generated with the Mann model, as explained in [6]. For both the offshore and the forest case the Mann turbulence box parameters are defined according to the IEC-61400-1 standard,  $\gamma = 3.9$  and  $L = 29.4$ . The wind turbine spacing as well as the yaw angle of the downstream wind turbine are varied to characterize the effect of yawing in a wake situation. Six ten-minutes simulations with different stochastic realisations (ie. based on different random seeds) per case are used to improve the statistical significance of the results. The investigated scenarios include mean wind speeds ranging from 4 m/s to 25 m/s.

The wake modeling in HAWC2 is based on the DWM model. The wind turbine wake includes the combination of three items: the wake deficit, the wake meandering and the wake self-generated turbulence. First, the wind turbine induction is computed for the given atmospheric condition, which results in a spatial averaged thrust profile. Then, the wake deficit evolution is computed based to the steady-state velocity and turbulence intensity as function of downstream position [10]. The HAWC2 DWM model has been validated against measurements from the Egmond aan Zee Wind Farm [15], and the power production has been compared to measurements and other engineering models in [16].

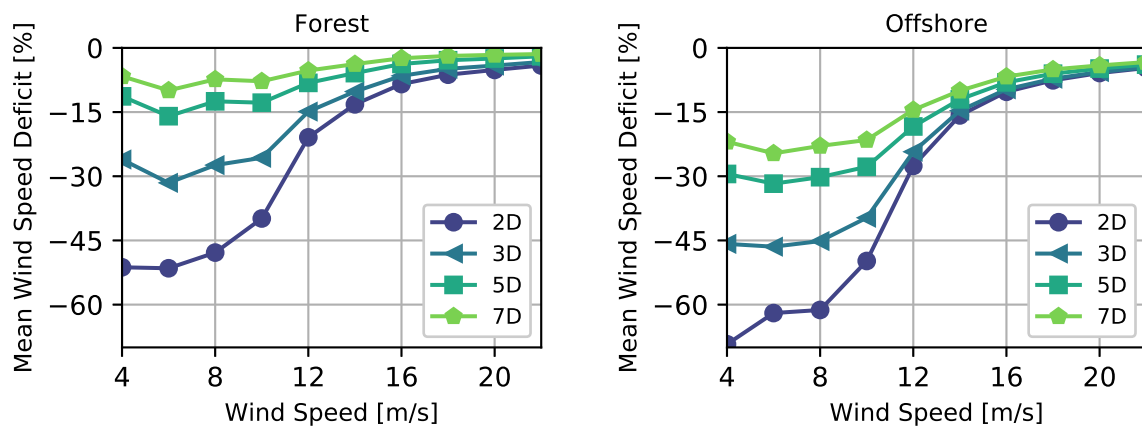
### 3. Results

The result section is divided in four parts. The first part describes the effect of the wake on the wind field immediately before an aligned downstream wind turbine as well as its effect on the power output of this wind turbine. The second part presents the power loss due to yaw misalignment, when a downstream wind turbine experiences the wind fields as described in the first section. The third part introduces the loss in annual energy production (AEP) obtained to characterize the power loss due to yaw misalignment. Finally, the model limitations are presented.

#### 3.1. Effect of wind turbine spacing on power production loss

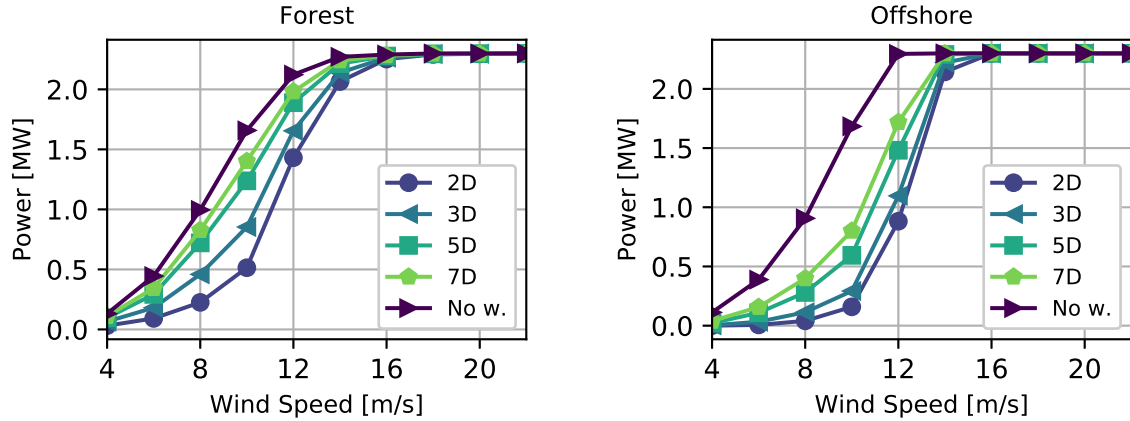
This section compares the influence of wind turbine spacing on the rotor mean wind speed and power output of downstream wind turbines. The rotor mean wind speed is defined as the wind speed averaged over time and space, i.e. over both the rotor plane and the duration of the simulation. The simulated results are generated for full wake conditions and no yaw misalignment.

First, the rotor mean wind speed deficit (relative to the free-stream case) is compared in Figure 1. In both the forest and offshore cases, it is possible to observe the wake recovery as a function of wind turbine spacing. As wind turbine spacing increases, the wind speed deficit observed by the downstream wind turbine decreases due to turbulent mixing. The rotor mean wind speed deficit is larger for the offshore cases compared to the forest case due to the lower offshore turbulent intensity, leading to modest mixing of the wake. This result is aligned with the formulation used in [10].



**Figure 1:** Influence of wake position on rotor-averaged wind speed deficit for respectively the forest and the offshore case for different downstream positions

The associated power output of the downstream wind turbine is compared in Figure 2. For both cases, the highest power production over all operating wind speeds is found in the no-wake case, whereas the lowest is obtained in the wake case with smallest the wind turbine inter-spacing. Close to rated power (11.2 m/s), the forest case produces less power than the offshore case. This phenomenon is a result of the higher turbulent intensity, which causes the power curve to be ‘smoothed out’ due to the large turbulent variations in wind speed. Conversely, at low wind speed, i.e. 8 m/s, the same effect causes the forest wind turbine to produce more than the offshore wind turbine.



**Figure 2:** Influence of wake position on electrical power production for the forest and the offshore case for different downstream wind turbine positions

### 3.2. The effect of yaw misalignment on power production loss in wake situations

Using the cases from the previous section as a reference, the downstream wind turbine is now yawed in order to quantify the effect of yaw on power production in wake situations. As shown above, the presence or absence of wake and the atmospheric conditions during below rated operation influence the power production. In order to model the power loss due to yaw misalignment, the power output is normalised against the aligned case. For a given yaw misalignment angle,  $\gamma$ , and power output of the downstream wind turbine,  $P(\gamma)$ , the normalised power output is defined as:

$$\eta(\gamma) = \frac{P(\gamma)}{P(0)}. \quad (1)$$

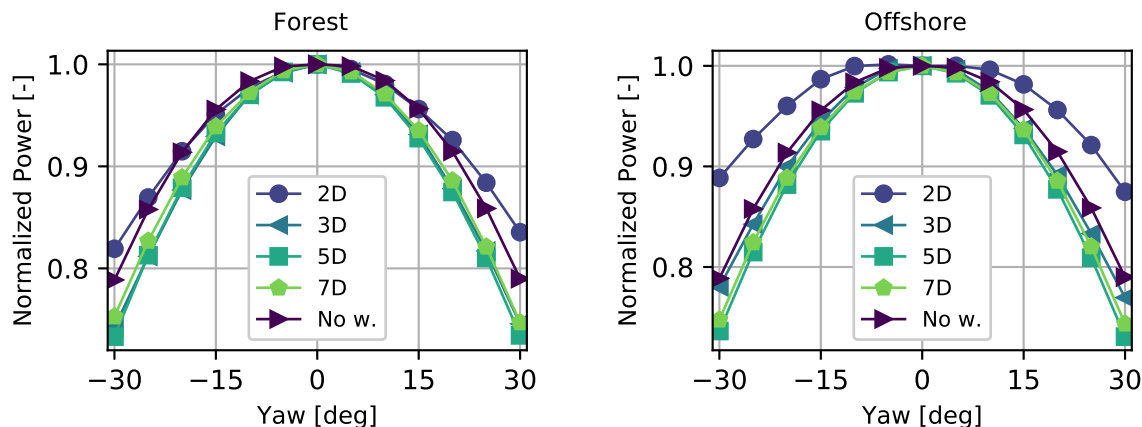
In accordance with other literature on power loss in yaw situations [3],  $\eta(\gamma)$  is parameterised using the approximation,

$$\eta(\gamma) \approx \cos^\alpha \gamma, \quad (2)$$

where  $\alpha$  is the fit exponent which describes  $\eta(\gamma)$  the best. Based on momentum theory, the value of  $\alpha$  is 3 [3]. However, in [4], it is reported that measurements involving both wind tunnel models and fullscale wind turbines tested at Vattenfall/FFA and DNW have indicated that the exponent may vary between 1.8 and 5.14 for the NREL Phase VI rotor. Such studies have also consistently shown that the BEM theory over predicts the power at yawed conditions. This is possibly related to the limitations of the linear momentum equation modified for yawed flows.

The sensitivity of the power as function of yaw angle is only relevant below rated wind speeds. For wind speeds higher than rated, the wind turbine produces rated power regardless the yaw misalignment. Thus, the analysis of  $\alpha$  in that region lacks interest because it corresponds to a fixed value of zero. The results for forest and offshore case at 6 m/s are presented in Figure 3 to ensure the wind turbine operation is below rated.

Figure 3 shows the relative power loss due to wake misalignment for the forest and offshore cases respectively. A free inflow simulation is also displayed, which provides the reference or no wake case. It can be observed for the forest case that the relative power loss in a yawed case is



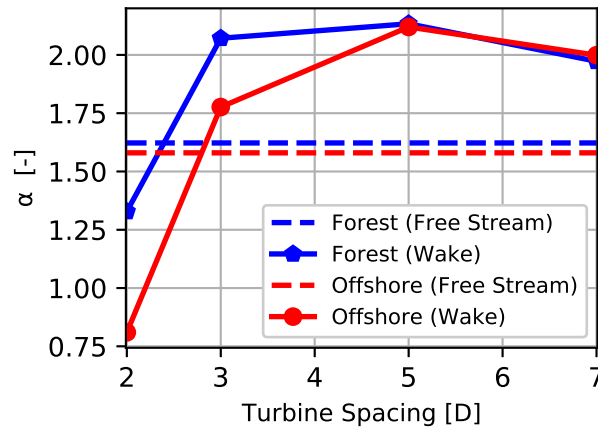
**Figure 3:** Power normalization for forest and offshore case at 6 m/s for different downstream distances

higher for the 3D, 5D and 7D while less power is lost if the wind turbines are placed 2D. For example, the 3D case at a yaw angle of  $-30^\circ$  presents a power reduction of 26%, i.e. produces only 74 % of the available power, while the free-stream case for the same angle presents a reduction of 21.5%. On the other hand, the 2D case shows a reduction of 17.5%, which is lower than the free-stream case. Therefore, it appears that the relative power loss due to yaw misalignment is diminished when a turbine is in a near-wake scenario. The cause of this surprising phenomenon is a result of the spatial distribution of the wake deficit, as explained below. It should be noted, however, that it is unlikely to observe turbine spacing less than 3D in modern wind farms.

Similarly, for the offshore case, the 2D case produces 88.5 % of the available power at a yaw angle of  $-30^\circ$ , while the freestream case produces slightly below 79%. The rest of the downstream distance, 3D, 5D and 7D, produces lower power than the free stream case. This phenomenon can be further explained by determining the relative power losses due to yaw, which can be obtained by computing the  $\alpha$  value in Equation 2 found by minimizing the sum of square errors between the fitting and the actual data.  $\alpha$  provides the sensitivity of power loss as function of yaw angle. The higher the value of  $\alpha$ , the higher the power loss for a given yaw angle. The  $\alpha$  fit for the offshore and forest case at 6 m/s is shown as function of wind turbine spacing in Figure 4.

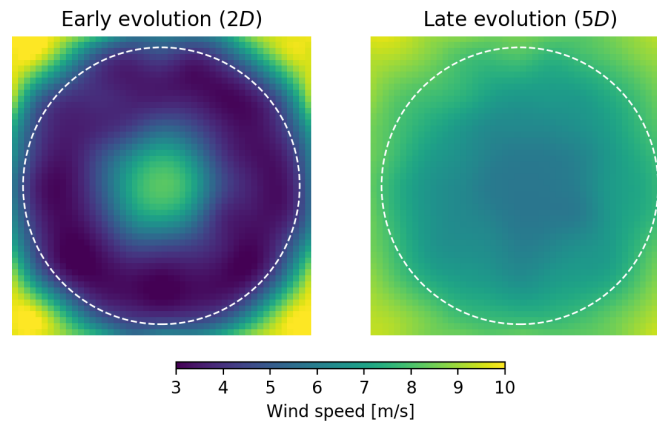
Figure 4 presents the  $\alpha$  fit as function of downstream distance for the free stream, offshore and forest case. The free stream value of  $\alpha$  is used as a reference. The  $\alpha$  value for the 2D downstream distance is lower in both the offshore and forest case compared to the free stream case, which can also be deduced from Figure 3 where the 2D case presents relatively lower power loss due to misalignment. In contrast,  $\alpha$  is larger than the freestream case for wind turbine spacings greater than 3D. The  $\alpha$  is expected to converge to the reference value for large wind turbine spacings, as the wake dissipates due to turbulent mixing.

In searching for an explanation of the variation of  $\alpha$  as a function of wind turbine spacing, it was found that  $\alpha$  is highly dependent on the radial distribution of wind speeds over the rotor plane, which corresponds to the shape of the wind field created by a wake. It is normally assumed that the wind field is homogeneous, or contains only vertical non-uniformity (such as wind shear or tower shadow). In these cases, yawing the wind turbine simply reduces the wind speed projected onto the rotor plane by a cosine factor. There is, in fact, an additional effect,



**Figure 4:**  $\alpha$  fit for free stream, offshore and forest case at 6m/s as function of downstream wind turbine spacing (distance normalized with wind turbine diameter)

which is that each point on the rotor point is, on average, shifted towards the center of the rotor plane. This commonly neglected effect, combined with a radial non-uniformity in the wind field due to yaw misalignment, can have a significant impact on the power output. An example of the flow observed from a downstream wind turbine is shown in Figure 5, where 2D and 5D can be observed. For low wind turbine spacing, a ring shaped wake exists, which causes low values of  $\alpha$ . As the ring shape dissipates,  $\alpha$  increases.



**Figure 5:** 10 minutes averaged wind fields observed from downstream wind turbine at 2D and 7D (forest case,  $U = 10\text{m/s}$ ).

### 3.3. Annual Energy Production Analysis

From the results above, it is clear that a combination of wind turbine spacing and turbulent mixing plays an important role on the power loss that occurs, when a wind turbine is yawed in a wake condition. To better quantify this, the reduction in annual energy production (AEP) is determined for varying wind turbine spacing while fixing the yaw misalignment to  $15^\circ$  as an example. The results of this analysis, shown in Table 1, illustrate a key finding in this paper.



Namely, the power loss is maximum at a wind turbine spacing of approximately 3D. Surprisingly, the relative power loss in a near wake scenario (2D) is lower than the 3D to 7D cases. This is due to the early evolution of the wake shape, which has a ring shape compared to a more mixed wake experienced at 3D and beyond as observed in Figure 5.

**Table 1:** Loss in AEP due to  $15^\circ$  yaw error in full wake situation (Weibull parameters,  $A = 8.46$ ,  $k = 2$ ).

Case	Wind turbine spacing ( $L_{long}$ )				
	No wake	2D	3D	5D	7D
Offshore	2.70%	2.97%	4.55%	4.48%	4.15%
Forest	3.24%	3.64%	4.95%	4.90%	4.50%

It should be noted that AEP calculations are performed for a fixed wind direction, which corresponds to a wake case. The analysis does not take into account the whole complexity of a wind farm, since multiple wake scenarios in such depends on the wind direction and farm layout.

### 3.4. Model Limitations

The results of this paper rely on The Dynamic Wake Meandering model in HAWC2 to propagate the wake in simulation. The Dynamic Wake Meandering model is a medium-fidelity engineering model capable of predicting the non-stationary wind farm flow field and thus the wake deficit and its dynamics behind a wind turbine. The limiting assumptions of the model [10] relevant to this paper relate to the near-wake approximation and radial symmetry. In the near wake regime - here assumed to extend to 3D downstream of the rotor plane - the wake is obtained by expanding the wake resulting from BEM modelling using a simple mass and momentum conserving pressure recovery approximation [11]. The model moreover assumes the wake deficit to be circular symmetric. Due to these simplifying assumptions, the complex behaviour in the near wake regime and non-rotationally symmetric wakes are not represented in this study. Additionally, the analysis in this paper assumes the wake intercepts the downstream wind turbine with no meandering in order to isolate the effect of the wake profile on power output. Meandering is not considered, but is a logical step in the future work of this investigation.

## 4. Conclusion and future work

The effect of power loss due to yaw misalignment in wake situations is presented in this paper using a 2.3MW wind turbine model simulated in HAWC2. Two contrasting site conditions, an offshore and forest case, are analysed to emphasise the consistency of the results despite large variations in the ambient turbulence intensity. In both atmospheric condition cases, a larger power reduction is found when there is yaw misalignment in a wake situation at least 3D downstream. On the other hand, yaw misalignment at distances below 3D present a lower reduction than the free stream case. To quantify this effect, the exponent term,  $\alpha$  is numerically determined, representing the power sensitivity to yaw misalignment.

Variations on  $\alpha$  are attributed to the wake deficit profile which varies due to two main factors: ambient turbulence intensity, and wind turbine spacing. Higher levels of turbulence intensity cause the wake to dissipate faster due to a higher rate of turbulent mixing, whereas larger wind turbine spacing provides a longer period for the mixing to occur. In the near wake region, the wake profile presents a bimodal diametric distribution, which is, surprisingly, found to increase

the power output of a downstream wind turbine when yawed. As the wake profile dissipates beyond the near wake region, the bimodal shape breaks down into a single coherent velocity deficit. Wind turbines in the region of approximately 4D-5D experience the greatest reduction in power output due to yaw misalignment.  $\alpha$  converges to the freestream value as wind turbine spacing increases further.

The presented results emphasize the importance of the wind turbine alignment in below rated conditions when in full wake conditions. In particular, the percentage reduction in AEP due to yaw misalignment is largest for wind turbines spaced at approximately 4D. The presented work provides valuable information for wind farm planning when wake situations are present.

## 5. Acknowledgements

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